Vulnerability to extreme heat by socio-demographic characteristics and area green space among the elderly in Michigan, 1990-2007

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Abstract

Objectives—We examined how individual and area socio-demographic characteristics independently modified the extreme heat (EH)-mortality association among elderly residents of 8 Michigan cities, May-September, 1990-2007.

Methods—In a time-stratified case-crossover design, we regressed cause-specific mortality against EH (indicator for 4-day mean, minimum, maximum or apparent temperature above 97th or 99th percentiles). We examined effect modification with interactions between EH and personal marital status, age, race, sex and education and ZIP-code percent "non-green space" (National Land Cover Dataset), age, race, income, education, living alone, and housing age (U.S. Census).

Results—In models including multiple effect modifiers, the odds of cardiovascular mortality during EH (99th percentile threshold) vs. non-EH were higher among non-married individuals (1.21, 95% CI = 1.14-1.28 vs. 0.98, 95% CI = 0.90-1.07 among married individuals) and individuals in ZIP codes with high (91%) non-green space (1.17, 95% CI = 1.06-1.29 vs. 0.98, 95% CI = 0.89-1.07 among individuals in ZIP codes with low (39%) non-green space). Results suggested that housing age may also be an effect modifier. For the EH-respiratory mortality

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association, the results were inconsistent between temperature metrics and percentile thresholds of EH but largely insignificant.

Conclusions—Green space, housing and social isolation may independently enhance elderly peoples' heat-related cardiovascular mortality vulnerability. Local adaptation efforts should target areas and populations at greater risk.

Keywords

heat wave; mortality; vulnerability; green space; socio-demographic

1. Introduction

In the U.S., the association between hot weather and mortality, especially cardiovascular and respiratory mortality, is well established (Anderson and Bell, 2009; Braga et al., 2002; Curriero et al., 2002; Medina-Ramon and Schwartz, 2007). With climate change and an aging population, heat-related mortality is of increasing concern. Public health measures to protect vulnerable populations from the effects of heat and heat waves are being adopted in many cities in the U.S. and around the world. Previously identified characteristics of vulnerability to heat-related morbidity and mortality include: advanced age, nonwhite race, poverty, lack of air conditioning or the financial resources to operate an air conditioner, social isolation, lack of green space (which provides shade and reduces ambient temperature) and low educational attainment (Reid et al., 2009; Sampson et al., 2013; Zanobetti et al., 2013). These characteristics have been used to construct vulnerability maps that can help communities determine where to focus resources during extreme heat (EH) (Harlan et al., 2013; Johnson et al., 2012; Reid et al., 2009).

However, in a validation study of one such vulnerability map, Reid and colleagues (Reid et al., 2012) showed that their map reflected vulnerability to mortality in general but not vulnerability to heat-associated mortality. Some previously constructed vulnerability maps have been limited by using data that identify the characteristics of vulnerability or the health outcome of interest at a spatial resolution no finer than city- or county-level. Additionally, some of the area-level characteristics evaluated, such as percent of people living in poverty, percent of people with lower education, and percent green-space can be highly correlated with each other. For example, in the Detroit metropolitan area, census tracts with lower percent of vegetative cover are often the same census tracts with the highest percent of residents in poverty (White-Newsome et al., 2009). Finally, it is likely that socio-demographic characteristics of heat vulnerability such as race, income and education are mediated by more downstream mechanisms of heat vulnerability, such as cultural and social isolation, poor housing or utility poverty (Gronlund, 2014). This situation makes evaluation of the independent and relative contributions of these factors to heat vulnerability challenging. In other words, the relative influence of each of these potential effect modifiers, as well as the extent to which these effect modifiers confound each other, is poorly understood.

Cities in Michigan, a state with a temperate, 4-season climate and relatively low air conditioning prevalence, have been shown to have high vulnerability to heat (Anderson and

Bell, 2009; Zanobetti and Schwartz, 2008). We aimed to determine the relative influence of individual and ZIP-code characteristics in modifying the short-term association between EH and cardiovascular and respiratory mortality in Michigan using death, land cover, temperature and socio-demographic data from 1990-2007.

2. Methods

2.1 Data

The 10 counties in Michigan with populations greater than 200,000 were aggregated into 8 "cities" according to the county's corresponding Metropolitan Statistical Area: Ann Arbor (Washtenaw County), Detroit (Wayne, Oakland and Macomb Counties), Flint (Genesee County), Grand Rapids (Kent County), Holland (Ottawa County), Kalamazoo (Kalamazoo County), Lansing (Ingham County) and Saginaw (Saginaw County) (Figure 1). Within these cities, we used ZIP codes, i.e., U.S. postal codes, as area units.

Michigan death records from 1990-2007 were obtained from the Michigan Department of Community Health. These records included date of death, ZIP code of residence, marital status, race, age, sex and educational level. We restricted our data set to decedents 65 years and older and further classified the decedents as unmarried vs. married or separated, black vs. nonblack (other race/ethnicities were too few to allow analysis), age 79 years or older vs. age 65-78 years, male vs. female and no high school degree vs. high school degree or higher. Primary causes of death were classified using the International Classification of Diseases codes from versions 9 and 10 (ICD-9 and ICD-10) as all-natural cause (ICD-9 < 800, 992 and E900.0; ICD-10 A-R, T67 and X30), heat-related (ICD-9 992 and E900.0; ICD-10 T67 and X30), cardiovascular (ICD-9 390-429; ICD-10 I0-I52) and respiratory (ICD-9 460-466, 480-487, 490-492, 494-496; ICD-10 J9-J18, J40-J44, J47).

Daily mean (TMEAN), minimum (TMIN) and maximum (TMAX) temperature and dew point (means of at least 18 hourly observations) were obtained from the National Climatic Data Center (2012c) for the airport weather station nearest to each city with the most complete time series. Daily mean apparent temperature (AT, °C), a measure which incorporates both temperature and humidity, was calculated as:

$$AT = -2.653 + (0.994 \times \text{ambient temperature}) + \left(0.0153 \times (\text{dew point temperature})^2\right)$$

(O'Neill et al., 2005)

For 4 of the study cities, Detroit, Grand Rapids, Flint and Lansing, ozone data from the U.S. Environmental Protection Agency's Air Quality System (U.S. EPA, 2007) were available from monitors in the corresponding counties. Daily 8-hour averages were calculated and standardized as described previously (Medina-Ramón et al., 2006).

We obtained area-level socio-demographic characteristics from 2 sources: Decennial Census Long Form data in 2000 ZIP Code Tabulation Areas (ZCTAs, polygons constructed by the U.S. Census Bureau approximating ZIP codes, which are not true polygons), for 1990 and 2000 (Geolytics, Inc., 2006) and 5-year average (2006-2010) estimates in 2010 ZCTA

boundaries from the American Community Survey (2012b). We extracted the following characteristics for each study ZIP code: percent 65 years or older and living alone; percent black; percent aged 75 years and older; percent without a high school degree; percent of households at or below the poverty level; and percent of homes built before 1940, 1940-1959, 1960-1979 and after 1979. We also obtained ZIP-code population-weighted centroids for 2000 and 2010 ZIP codes (MABLE/Geocorr, 2012).

Land cover classifications at a resolution of 30×30 m were obtained from the Multi-Resolution Land Characteristics Consortium for 1992, 2001 and 2006 (U.S. Department of the Interior, 2012). We further classified these data as "green space" vs. "non-green space" (Figure 1) and calculated the percent area non-green space in each ZIP code using ZIP Code Tabulation Area 2000 and 2010 Census TIGER/Line shapefiles (2010 Census, 2012) in ArcGIS 10.1.

We estimated annual values for land cover and socio-demographic characteristics for each ZIP code by linearly interpolating the decadal values. For example, 1993 land cover values were obtained by taking a weighted average of the 1992 and 2001 values. For years outside the available data interval we used the annual value of the closest available year (e.g., land cover values for years 1990-1991 were estimated using the 1992 land cover value).

2.2 Analysis

We employed a time-stratified case-crossover design, implemented using conditional logistic regression in the coxph package in R 2.15, with controls selected on the same days of the week in the same month as the cases (except the case day) (Janes et al., 2005). Confounding by individual-level characteristics and characteristics that vary over durations longer than 1 month are automatically controlled for in this matched design. First, we examined the association between deaths and 4 temperature terms, 2-day means of AT (lag days 0-1, 2-3, 4-5 and 6-7), all used simultaneously and modeled using natural cubic splines (ns) with 6 degrees of freedom (df). Lags of 2-day mean AT, instead of single-day AT, were used to reduce collinearity between the temperature exposures:

$$logit\,(\text{mortality}) = ns\,(AT_{0-1}, df=6) + ns\,(AT_{2-3}, \mathbf{df}=6) + ns\,(AT_{4-5}, df=6) + ns\,(AT_{6-7}, df=6) \quad [1]$$

The results of these models were used to make decisions about the thresholds for EH as well as the number of lags to include in subsequent models. Specifically, we observed that AT above the 97th percentile of AT and at lag days 0-1 and 2-3 were significantly and strongly associated with mortality, while AT at subsequent lags was only weakly or not-significantly associated with mortality. By modeling temperature exposure as an indicator variable (EH vs. non-EH) in subsequent models, we were able to reduce our data set to only the discordant case-control sets, or instances where the cases had different daily exposures than their corresponding controls, because only discordant sets contribute information in a matched design. This eliminated 90% of the rows from our data set, making the following analyses of effect modification computationally feasible.

Next, to understand the EH effect across our entire study population and in each city, for each cause of death (cardiovascular or respiratory), using 2 EH thresholds (97th or 99th percentile of 4-day mean AT), we modeled:

$$logit\,(\text{mortality}) = \beta_1 EH03 + \beta_2\,(EH03 \times CITY2) + \ldots + \beta_8\,(EH03 \times CITY8) \quad [2]$$

where EH03 was an indicator variable for the mean of AT over lag days 0-3 being above the EH threshold in that city. CITY2 through CITY8 were indicator variables for each of the 8 cities, with Detroit as the reference city (CITY1). To test for confounding by ozone, we included a term for the mean of daily ozone over lag days 0-1 or lag days 0-3.

We then assessed effect modification (vulnerability) by including interaction terms between the time-varying exposure (AT) and each potential individual-level or ZIP-code-level effect modifier (Carracedo-Martinez et al., 2010):

$$logit\,(\text{mortality}) = \beta_1 EH03 + \beta_2\,(EH03 \times EM) + \beta_3\,(EH03 \times CITY2) + \ldots + \beta_9\,(EH03 \times CITY8) \quad [3]$$

where EM was the effect modifier. We modeled potential modifiers from each vulnerability category of age, race, sex, income, education, social isolation, building age and green space at each level at which they were available (individual or ZIP code). Individual-level effect modifiers (e.g., non-married) were represented in the model as indicator variables and effects were estimated for individuals with or without the characteristic. For the continuous effect modifiers, we estimated effects among individuals in the 25th and 75th percentile of that modifier. The percentiles of each effect modifier were calculated among the cases across all 8 cities (Table 1).

Based on results from the above models, we made the following decisions regarding the terms to use in in subsequent models with multiple effect modifiers. We included all the individual-level characteristics because we believed, *a priori*, that the individual-level characteristics mutually confounded each other. We also included the ZIP-code-level characteristics that had been found to be significant modifiers of the EH-mortality association in the single-effect-modifier models. However, because non-green space, poverty and housing age were strongly correlated with each other, including them all in the same model could substantially inflate their variances. Therefore, we also ran models that did not include all of these characteristics, with the caveat that these characteristics may be proxies for some other components that were strongly correlated but omitted from the model. The final models, with e.g., 11, potential effect modifiers, were of the form:

$$logit\,(\text{mortality}) = \beta_1 EH03 + \beta_2\,(EH03 \times EM_1) + \beta_3\,(EH03 \times EM_2) + \ldots + \beta_{12}\,(EH03 \times EM_{11})$$
$$+ \beta_{13}\,(EM03 \times CITY2) + \ldots + \beta_{19}\,(EH03 \times CITY8) \quad [4]$$

The odds of mortality during EH vs. non-EH were estimated for each effect modifier as the sum of the model's products of the βs (including β₁) and corresponding covariate values, where the effect modifier of interest took a value of 1 or 0 (for the indicator variables) or the 75th or 25th percentile (for the continuous variables), while the other effect modifiers in the model were set to equal the means among the cases. In sensitivity analyses, the models with a single modifier (Equation 3) and the models with multiple modifiers (Equation 4) were

fitted again using TMEAN, TMIN or TMAX in place of AT. We also modeled a three-way interaction between EH, non-married and sex given the possibility that effect modification by sex may be stronger among non-married individuals.

In city-specific analyses, to assess whether residual spatial correlation was still present, we derived the conditional logistic regression residuals for each matched set with identical characteristics using the SAS macro mcstrat (Vierkant et al., 2000). We then constructed the empirical semi-variograms of the residuals using the centroid of each matched set's ZIP code to calculate distances and we evaluated them for indication of residual spatial dependence in the data using the fields and gstats packages in R 2.15.

3. Results

After merging the ZIP code of residence in the death records with the corresponding ZIP-code socio-demographic and land cover data, we retained 99% of the deaths records in the 8 study cities, May-September, 1990-2007. With the exception of Holland, the 8 cities considered in this study were similar to one another with respect to temperature and individual characteristics (Table 1). In Holland, the percent of decedents who were black in each ZIP code was very small, ranging from 0.2% to 1.4%. Additionally, the percent of deaths coded as heat-related was too small in any city to use this cause of death as an outcome.

ZIP-code characteristics ranged more widely than temperature and individual characteristics between cities (Table 1). Ann Arbor ZIP codes had little non-green space (the 75th percentile of percent non-green space was 29.7%) while Detroit ZIP codes had a high percentage of non-green space (the 25th percentile was 68.9%). Among the ZIP-code characteristics, percent below the poverty level, percent black, percent without a high school degree and percent of homes built before 1940 were moderately to highly correlated with each other (Table 2).

In analyses of the association between EH and mortality without accounting for effect modification, effects were strongest for apparent temperature above the 97th percentile on lag days 0-1 and 2-3 (e.g., in Detroit, Figure 2 and in Grand Rapids, Figure A.1). In light of this result, in our effect modification analyses we modeled EH exposure as the mean of lag days 0-3 above the 97th or 99th percentile threshold.

In models with a single term for EH over lag days 0-3 and no effect modifiers, the odds ratio of cardiovascular mortality during EH vs. non-EH was 1.08 (95% CI = 1.05-1.11) and 1.14 (95% CI = 1.09-1.19) for EH defined at the 97th and 99th percentiles, respectively (Table 3). However, the odds of respiratory mortality during EH vs. non-EH were not increased (OR = 1.01, 95% CI = 0.94-1.07 for EH defined at the 97th percentile and OR = 1.05, 95% CI = 0.95-1.16 for EH defined at the 99th percentile, Table 3). Although the effects of EH diminished in models controlling for ozone, we did not consider ozone to be an important confounder of the EH-mortality association given that the ORs did not decrease by more than 10% (Table 3). EH effects were significantly lower in Flint as compared to Detroit (Table 4). However, in subsequent models accounting for individual- and ZIP-code-level

characteristics, all the city-specific effects were no longer significantly different from those in Detroit (results not shown).

Among the vulnerability characteristics, when each was examined by itself in a separate model, the individual characteristics non-married and black race and the ZIP-code characteristics percent non-green space, percent black, percent below poverty level, percent with no high school degree, percent of homes built before 1940 and percent of homes built 1940-1959 significantly increased the association between EH and cardiovascular mortality when EH was defined as 4-day AT average above the 97th and/or 99th percentile (Figures 3A, 3C). With the exception of black race, these effects were stronger for EH defined as being above the 99th percentile than above the 97th percentile. In these single effect modifier models, we did not find effect modification of the association between EH and respiratory mortality, with the exception of black race, which increased the association between EH defined at the 97th percentile and respiratory mortality (Figure 3B, 3D).

When we modeled EH based on TMIN, TMEAN and TMAX, our results were similar for cardiovascular mortality, with the following exceptions (Figures A.2, A.3 and A.4). The individual characteristic non-married was not a significant modifier in the TMAX or TMIN models. However, for TMAX and TMIN, percent of residents in a ZIP code 65 or older and living alone was associated with a significant reduction in the EH-mortality association.

For respiratory mortality, the results were inconsistent between the different temperature metrics (Figures A.2, A.3 and A.4). Non-married and black race, at the individual level, and percent black, percent below poverty and percent no high school, at the ZIP-code level, significantly decreased the EH-mortality association when EH was based on TMIN. When EH was based on TMAX, percent below poverty also significantly increased the EH-mortality association. When EH was based on TMEAN, non-married and percent of residents 65 and older and living alone significantly increased the EH-mortality association. The magnitude and significance of these EH-respiratory mortality modifiers also differed depending on the EH percentile threshold (Figures A.2, A.3 and A.4).

For models containing all 11 modifiers, being non-married and the ZIP-code percent non-green space modified the EH-cardiovascular mortality association, controlling for the other characteristics (Table 5). When EH was defined as AT above the 99th percentile, the odds of cardiovascular mortality among non-married individuals were 1.21 (95% CI = 1.14-1.28) times higher during EH than during non-EH as compared to 0.98 (95% CI = 0.90-1.07) among married individuals. The odds of cardiovascular mortality among individuals living in ZIP codes in the 75th percentile of non-green space (91% non-green space) were 1.17 (95% CI = 1.06-1.29) times higher during EH vs. non-EH as compared to 0.98 (95% CI = 0.89-1.07) among individuals in the 25th percentile of non-green space (39% non-green space). In a model omitting non-green space, the percent of homes built from 1940-1959 also modified the EH-cardiovascular mortality association (OR = 1.06, 95% CI = 0.99-1.14 among individuals in ZIP codes with a high percent of homes built from 1940-1959 as compared to OR = 0.98, 95% CI = 0.88-1.09 among individuals in ZIP codes with an equal percent of homes built in each category).

The association between EH and respiratory mortality was not significantly modified by any of these characteristics in models containing multiple effect modifiers (results not shown). Furthermore, we did not find residual spatial autocorrelation in analyses of the residuals. We also did not see a significant three-way interaction between EH, non-married and sex.

Results for effect modification when EH was based on TMEAN were similar to those for AT, but differed when EH was based on TMIN and TMAX. For TMIN, in models without percent non-green space, the percent of homes built before 1940 was a significant modifier, but other characteristics were not. When EH was based on TMAX, the ZIP-code percent green space significantly increased the EH-cardiovascular mortality association. However, the percent of residents 65 or older and living alone significantly reduced the EH-cardiovascular mortality association, and non-married and ZIP-code housing age were not significant modifiers.

4. Discussion

EH was associated with elevated cardiovascular mortality among elderly people in 8 Michigan cities, and depending on whether EH was based on AT, TMEAN, TMIN or TMAX, higher associations were observed for those who were not married and those living in ZIP codes with less green space, more residents aged 65 or older and living alone, and more homes built before 1960. We evaluated potential effect modification by multiple individual- and area-level variables, both one at a time and all together in a single model, an approach that has been rarely applied to date in heat epidemiology. Several of these variables were moderately correlated, reinforcing the need to account for confounding among effect modifiers when assessing vulnerability to heat. Even after accounting for race, education, age and sex to the extent that this information was available at the individual and area level, the effects of being non-married and the effects of certain ZIP-code characteristics persisted.

The positive association between non-green space and heat-associated mortality in Michigan is consistent with some, but not all, results from other epidemiologic studies evaluating whether heat-health associations differ by land cover or satellite-derived land surface temperature, and socio-demographic characteristics, measured at a fine geographic resolution. In a study of the 2005 summer in Phoenix, both percent impervious surface and land surface temperature in a census block group were associated with heat distress calls, controlling for a variety of other socio-demographic factors (Uejio et al., 2011). However, in a similar study of the 1999 summer in Philadelphia, none of the built environment measurements—vegetation, land surface temperature or percent impervious surface—were associated with heat deaths in a census block group (Uejio et al., 2011). In a separate study of Phoenix heat deaths in census block groups from 2000-2008, models incorporating either vegetation or land surface temperature in conjunction with socio-demographic factors best fit the data (Harlan et al., 2013). A case-only study of U.S. Medicare beneficiaries found increased mortality with warm-season temperature among individuals of nonwhite race and in ZIP codes with low green space, high population density and low education (Zanobetti et al., 2013). Finally, a case-crossover study in Worcester, Massachusetts evaluating individual- and area-level effect modifiers of the warm temperature-mortality association

found modification by area poverty and population density, but not by vegetation (Madrigano et al., 2013). However, these last two studies evaluated the effect modifiers individually and could not account for confounding among the modifiers.

Outside of the U.S., in Montreal, satellite-derived land surface temperature in a postal code modified the association between warm season temperature and daily mortality among individuals in postal codes with higher property values, but land surface temperature did not modify this association in postal codes with lower property values, where the temperature-mortality association was higher in general. This suggested an influence of the urban heat island effect on heat-associated mortality, though only in the absence of substantial socioeconomic deprivation (Smargiassi et al., 2009). In Kaohsiung City, Taiwan, mean temperature was associated with daily mortality only in regions of the city classified as having a high thermal load and low ventilation based on wind conditions, topography, land use, an urban heat island index and vegetation (Goggins et al., 2013). In Barcelona, Spain, researchers used a case-crossover design similar to ours with the individual-level effect modifiers of sex and age, 8 census-tract-level socio-demographic characteristics and percent tree cover in a buffer of 500 m around the decedent's address. In their final model, they retained the census-tract-level percentage of manual workers, old buildings and perception of surrounding greenness as significant modifiers of the association between mortality and three days of EH, although the percent tree cover measure was not a significant modifier (Xu et al., 2013). Our study, which also used a design that allowed us to control for both individual-level demographic factors and area-level factors, still showed a deleterious effect of lack of vegetation. These findings suggest that urban-heat-island mitigation strategies, such as increasing urban vegetation via tree planting programs, could be a useful adaptive strategy.

Few studies have explicitly evaluated the role of green space in human health. In addition to the studies of vegetation and heat-associated morbidity and mortality mentioned above, self-reported health and well-being indicators have been positively associated with green space (de Vries et al., 2003; Maas et al., 2006; Takano et al., 2002; Tanaka et al., 1996). A study in England found a significant difference in the association between income inequality and mortality across groups with differing exposure to green space. Respective incidence rate ratios for all-cause mortality and circulatory diseases were higher for residents living in less green areas than in areas with more green space (Mitchell and Popham, 2008). Green areas may protect health by reducing air pollution and the urban heat island effect and promoting physical activity for a healthier lifestyle.

Our analysis of vulnerability to heat-associated respiratory mortality was limited by the low number of daily respiratory deaths (7 per day). The characteristics of heat-associated respiratory mortality differed depending on how EH was defined and were not consistent with the corresponding characteristics of vulnerability identified for heat-associated cardiovascular mortality. The differences in characteristics of vulnerability to heat-associated respiratory mortality as compared to cardiovascular mortality may be due to differences in the underlying health conditions leading to death of respiratory vs. cardiovascular causes. For example, blacks may tend to have significantly more of the underlying health problems leading to heat-associated respiratory death than whites

(American Lung Association, 2010). Furthermore, although we did not find substantial confounding by daily city-specific ozone levels, heat-associated respiratory mortality may be modified by ozone exposure which may also differ by ZIP code, and this is a subject for further research.

Other limitations in our study were that the number of decedents of races other than black and white was too small in Michigan to evaluate effect modification, and the lack of availability of individual-level health and socio-demographic indicators besides age and marital and educational status prevented us from understanding how individual-level cultural or economic characteristics may confound the observed effect modification by race. Our study was limited by the still relatively coarse spatial resolution (ZIP code) of the case location of residence. The relative importance of, for example, having a tree above your house vs. a lush park down the street cannot be disentangled at the ZIP code level. Future research will use more finely resolved spatial information and will develop methods to map of vulnerability to heat in Michigan. Additionally, more finely resolved spatial information may elucidate the roles of area-level measures of elderly residents living alone and housing age—results which were sensitive to modeling assumptions in the present analysis.

Our finding that being unmarried was a significant characteristic of heat vulnerability was consistent with other research, particularly studies of the 1995 Chicago heat wave that reported social isolation as a characteristic of vulnerability to heat and heat waves (Klinenberg, 2002; Sampson et al., 2013; Semenza, 1996). However, we were limited in not knowing whether the non-married cases were in fact more socially isolated than the married cases. That the ZIP-code percent of residents 65 or older and living alone significantly decreased the heat-mortality association in some models was surprising, but we speculate that this characteristic may be a proxy for living in senior housing and receiving services during EH.

Although we lacked individual-level or ZIP code-level information about air conditioning prevalence, previous research has found that having the financial resources to operate an air conditioner is important in addition to owning an air conditioner (Klinenberg, 2002; Sampson et al., 2013; Sheridan, 2007). Percentage of residents below the poverty level may therefore, to some extent, capture air conditioning usage at the ZIP code level. Nevertheless, the absence of finer scale information about income and air conditioning usage is a significant limitation of this and other studies of heat vulnerability.

5. Conclusions

Being non-married and living in areas with little green-space, few elderly residents living alone and a high percentage of homes built before 1960 were associated with increased vulnerability to EH-associated cardiovascular mortality in Michigan, even after controlling for both individual and area socio-demographic characteristics. These findings, and those of other extant and future studies which evaluate multiple, potentially correlated, effect modifiers simultaneously, may help guide local hot weather adaptation strategies to intervene on key vulnerability factors.

Acknowledgments

Appendix

Table A.1

Odds ratios (ORs) and 95% confidence intervals for the odds of cardiovascular mortality during extreme heat (EH, the 99th percentile of mean *daily mean* temperature over lag days 0-3) vs. non-EH among elderly individuals without (low) or with (high) a given individual characteristic or elderly individuals residing in ZIP codes in the 25th (low) or 75th (high) percentiles of the ZIP-code characteristic, with multiple interactions per model, in 8 cities in Michigan, May-September, 1990-2007.

Term	Model 1		Model 2		Model 3		N
	Low	High	Low	High	Low	High	I
Non-married	1.04 (0.95-1.13)	1.21 (1.14-1.29)[***]	1.04 (0.95-1.13)	1.21 (1.14-1.28)[***]	1.04 (0.95-1.13)	1.21 (1.14-1.29)[***]	1
No high school	1.14 (1.06-1.21)	1.04 (0.96-1.13)[*]	1.14 (1.06-1.22)	1.04 (0.96-1.13)[*]	1.14 (1.06-1.21)	1.04 (0.96-1.13)[*]	1
Male	1.06 (0.98-1.15)	1.15 (1.07-1.24)[*]	1.06 (0.98-1.15)	1.15 (1.07-1.24)[*]	1.06 (0.98-1.15)	1.15 (1.07-1.24)[*]	1
Black	1.08 (1.01-1.15)	1.22 (1.06-1.4)	1.08 (1.02-1.15)	1.19 (1.04-1.35)	1.08 (1.01-1.15)	1.21 (1.05-1.39)	1
Age 79+	1.11 (1.02-1.2)	1.09 (1.02-1.17)	1.11 (1.02-1.2)	1.09 (1.02-1.18)	1.11 (1.02-1.20)	1.09 (1.02-1.17)	1
% Non-green	0.98 (0.89-1.07)	1.27 (1.15-1.4)[***]	0.99 (0.9-1.08)	1.25 (1.14-1.38)[***]	0.99 (0.91-1.08)	1.25 (1.15-1.36)[***]	
% 65 and alone	1.12 (1.05-1.20)	1.08 (1.02-1.15)	1.12 (1.05-1.20)	1.08 (1.02-1.15)	1.12 (1.05-1.2)	1.09 (1.02-1.16)	1
% Below poverty	1.13 (1.04-1.22)	1.08 (1.01-1.16)			1.11 (1.03-1.19)	1.09 (1.03-1.17)	1
% Built < 1940	1.11 (0.99-1.25)	1.17 (1.03-1.33)	1.10 (0.98-1.23)	1.13 (1.02-1.26)			1
% Built 1940-1959	1.11 (0.99-1.25)	1.09 (1.01-1.17)	1.10 (0.98-1.23)	1.08 (1.01-1.16)			1
% Built 1960-1979	1.11 (0.99-1.25)	1.14 (1.06-1.23)	1.10 (0.98-1.23)	1.13 (1.05-1.22)			1

Significance of interaction term:

[**] p < 0.05

[*] p < 0.10

[***] p < 0.001.

Table A.2

Odds ratios (ORs) and 95% confidence intervals for the odds of cardiovascular mortality during extreme heat (EH, the 99th percentile of mean *daily minimum* temperature over lag days 0-3) vs. non-EH among elderly individuals without (low) or with (high) a given individual characteristic or elderly individuals residing in ZIP codes in the 25th (low) or 75th (high) percentiles of the ZIP-code characteristic, with multiple interactions per model, in 8 cities in Michigan, May-September, 1990-2007.

Term	Model 1		Model 2		Model 3		Mode
	Low	High	Low	High	Low	High	Low
Non-married	1.02 (0.93-1.12)	1.13 (1.06-1.21)[*]	1.02 (0.93-1.12)	1.13 (1.06-1.21)[*]	1.02 (0.93-1.12)	1.14 (1.07-1.21)[*]	1.02 (
No high school	1.08 (1.01-1.16)	1.03 (0.94-1.12)	1.08 (1.01-1.16)	1.03 (0.94-1.12)	1.08 (1.01-1.16)	1.03 (0.94-1.12)	1.08 (
Male	1.05 (0.96-1.14)	1.08 (1.00-1.16)	1.05 (0.96-1.14)	1.08 (1-1.16)	1.05 (0.96-1.14)	1.08 (1.00-1.16)	1.05 (
Black	1.05 (0.98-1.12)	1.13 (0.97-1.31)	1.06 (0.99-1.13)	1.08 (0.94-1.23)	1.05 (0.98-1.12)	1.14 (0.98-1.32)	1.05 (
Age 79+	1.08 (0.99-1.17)	1.04 (0.97-1.13)	1.08 (0.99-1.17)	1.05 (0.97-1.13)	1.08 (0.99-1.18)	1.05 (0.97-1.13)	1.08 (
% Non-green	1.00 (0.91-1.1)	1.14 (1.02-1.26)	1.02 (0.93-1.12)	1.11 (1-1.23)	0.97 (0.89-1.06)	1.17 (1.07-1.28)[***]	
% 65 and alone	1.07 (1,00-1.15)	1.05 (0.98-1.12)	1.07 (1.00-1.15)	1.05 (0.98-1.12)	1.08 (1.01-1.16)	1.05 (0.98-1.12)	1.06 (
% Below poverty	1.11 (1.02-1.21)	1.03 (0.96-1.10)			1.08 (1.00-1.17)	1.05 (0.98-1.12)	1.10 (
% Built < 1940	1.05 (0.93-1.19)	1.16 (1.01-1.33)	1.03 (0.91-1.17)	1.09 (0.97-1.22)			1.01 (
% Built 1940-1959	1.05 (0.93-1.19)	1.09 (1.01-1.17)	1.03 (0.91-1.17)	1.08 (1.00-1.16)			1.01 (
% Built 1960-1979	1.05 (0.93-1.19)	1.06 (0.98-1.15)	1.03 (0.91-1.17)	1.04 (0.97-1.13)			1.01 (

Significance of interaction term:

[*] p < 0.10

[**] p < 0.05

[***] p < 0.001.

Table A.3

Odds ratios (ORs) and 95% confidence intervals for the odds of cardiovascular mortality during extreme heat (EH, the 99th percentile of mean *daily maximum* temperature over lag days 0-3) vs. non-EH among elderly individuals without (low) or with (high) a given individual characteristic or elderly individuals residing in ZIP codes in the 25th (low) or 75th (high) percentiles of the ZIP-code characteristic, with multiple interactions per model, in 8 cities in Michigan, May-September, 1990-2007.

Term	Model 1		Model 2		Model 3		M
	Low	High	Low	High	Low	High	L
Non-married	1.07 (0.98-1.17)	1.18 (1.11-1.25)	1.07 (0.98-1.17)	1.18 (1.11-1.25)[*]	1.07 (0.98-1.17)	1.18 (1.11-1.25)	1
No high school	1.14 (1.06-1.22)	1.07 (0.98-1.16)	1.14 (1.06-1.22)	1.07 (0.98-1.16)	1.14 (1.06-1.22)	1.07 (0.98-1.16)	1
Male	1.09 (1.01-1.19)	1.13 (1.05-1.22)	1.09 (1.01-1.19)	1.13 (1.05-1.22)	1.09 (1.01-1.18)	1.13 (1.05-1.22)	1
Black	1.11 (1.04-1.18)	1.11 (0.96-1.28)	1.11 (1.04-1.18)	1.13 (0.99-1.29)	1.11 (1.04-1.18)	1.10 (0.95-1.27)	1
Age 79+	1.16 (1.07-1.26)	1.08 (1.00-1.16)	1.16 (1.07-1.26)	1.08 (1.00-1.16)	1.16 (1.06-1.25)	1.08 (1.00-1.16)	1
% Non-green	0.99 (0.90-1.09)	1.28 (1.16-1.42)[***]	0.98 (0.89-1.08)	1.29 (1.17-1.42)[***]	1.00 (0.92-1.09)	1.26 (1.15-1.37)[***]	
% 65 and alone	1.18 (1.10-1.26)	1.07 (1.01-1.14)[***]	1.18 (1.10-1.26)	1.07 (1.01-1.14)[***]	1.17 (1.09-1.26)	1.07 (1.01-1.14)[***]	1

Term	Model 1		Model 2		Model 3		M
	Low	High	Low	High	Low	High	L
% Below poverty	1.09 (1.00-1.19)	1.12 (1.05-1.20)			1.08 (1.00-1.16)	1.13 (1.06-1.21)	1
% Built < 1940	1.11 (1.00-1.25)	1.17 (1.03-1.33)	1.12 (1.01-1.25)	1.19 (1.07-1.33)			1
% Built 1940-1959	1.11 (1.00-1.25)	1.09 (1.02-1.17)	1.12 (1.01-1.25)	1.10 (1.02-1.18)			1
% Built 1960-1979	1.11 (1.00-1.25)	1.15 (1.07-1.24)	1.12 (1.01-1.25)	1.16 (1.07-1.25)			1

Significance of interaction term:

*
 $p < 0.10$

**
 $p < 0.05$

***
 $p < 0.001$.

Figure A.1.
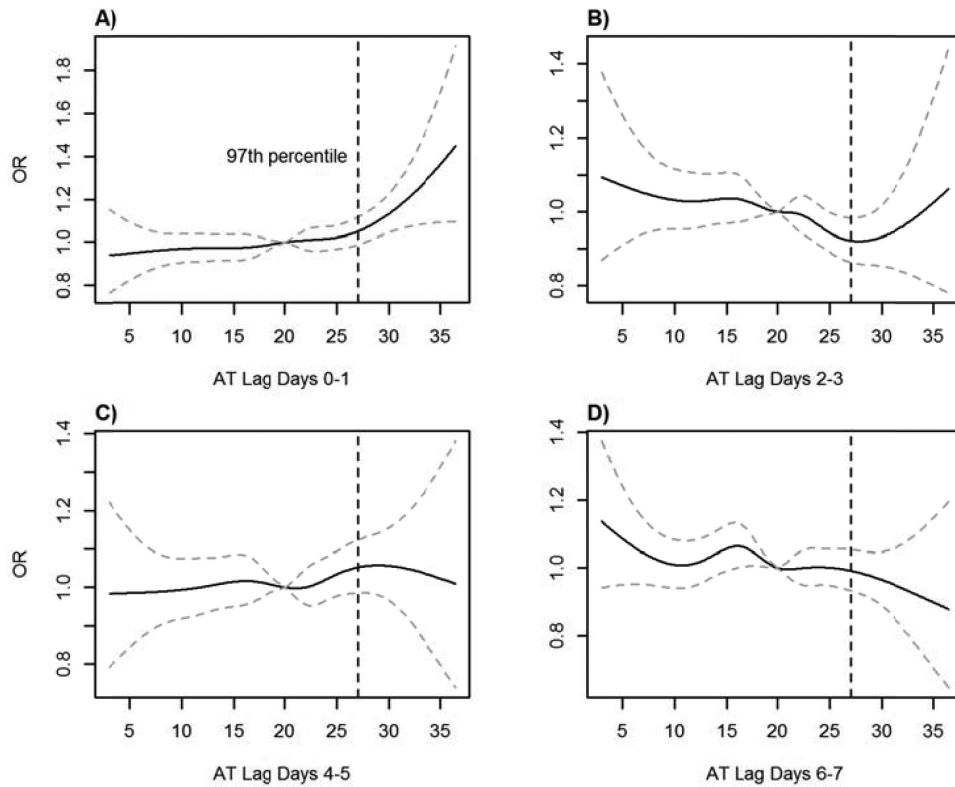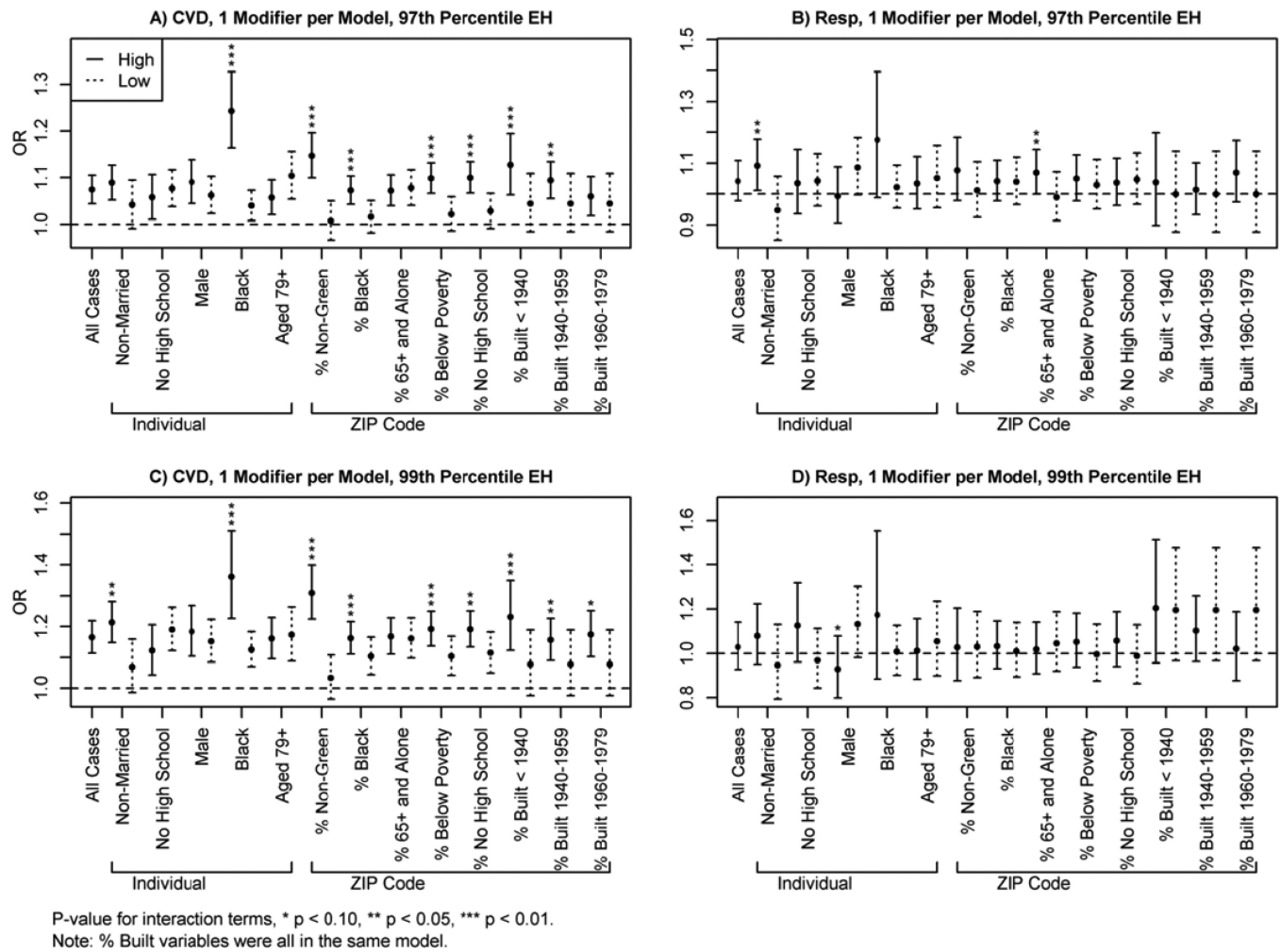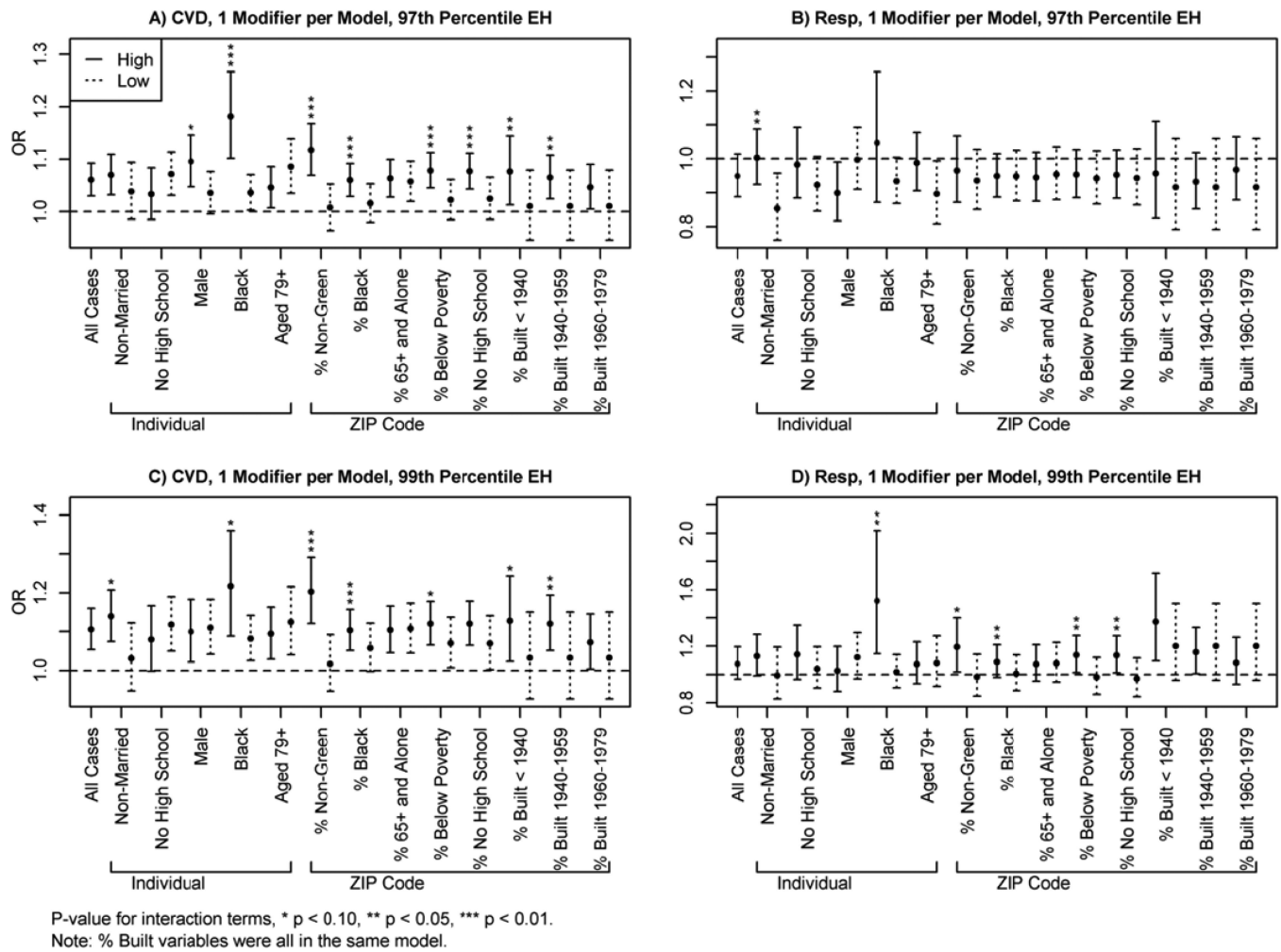Odds ratios (ORs) and 95% confidence intervals for the odds of cardiovascular morality among elderly individuals and 4 2-day lags (lags 0-1, 2-3, 4-5, 6-7) of apparent temperature relative to 20 °C, modeled simultaneously as 4 natural cubic splines (each with 6 degrees of freedom), *Grand Rapids*, Michigan, 1990-2007. (Dashed line represents the 97th percentile threshold of 2-day apparent temperature in Grand Rapids).

Figure A.2.
Odds ratios (ORs) and 95% confidence intervals for the odds of mortality (cardiovascular, CVD, or respiratory, RESP) during extreme heat (EH, the 97th or 99th percentiles of mean *daily mean* temperature over lag days 0-3) vs. non-EH among either all individuals, individuals without (low) or with (high) a given individual characteristic, or individuals residing in ZIP codes in the 25*th* (low) or 75*th* (high) percentiles of the ZIP-code characteristic among the elderly in 8 cities in Michigan, May-September, 1990-2007.

P-value for interaction terms, * p < 0.10, ** p < 0.05, *** p < 0.01.
Note: % Built variables were all in the same model.

Figure A.3.
Odds ratios (ORs) and 95% confidence intervals for the odds of mortality (cardiovascular, CVD, or respiratory, RESP) during extreme heat (EH, the 97th or 99th percentiles of mean *daily minimum* temperature over lag days 0-3) vs. non-EH among either all individuals, individuals without (low) or with (high) a given individual characteristic, or individuals residing in ZIP codes in the 25th (low) or 75th (high) percentiles of the ZIP-code characteristic among the elderly in 8 cities in Michigan, May-September, 1990-2007.

P-value for interaction terms, * p < 0.10, ** p < 0.05, *** p < 0.01.
Note: % Built variables were all in the same model.

Figure A.4.
Odds ratios (ORs) and 95% confidence intervals for the odds of mortality (cardiovascular, CVD, or respiratory, RESP) during extreme heat (EH, the 97th or 99th percentiles of mean *daily maximum* temperature over lag days 0-3) vs. non-EH among either all individuals, individuals without (low) or with (high) a given individual characteristic, or individuals residing in ZIP codes in the 25th (low) or 75th (high) percentiles of the ZIP-code characteristic among the elderly in 8 cities in Michigan, May-September, 1990-2007.
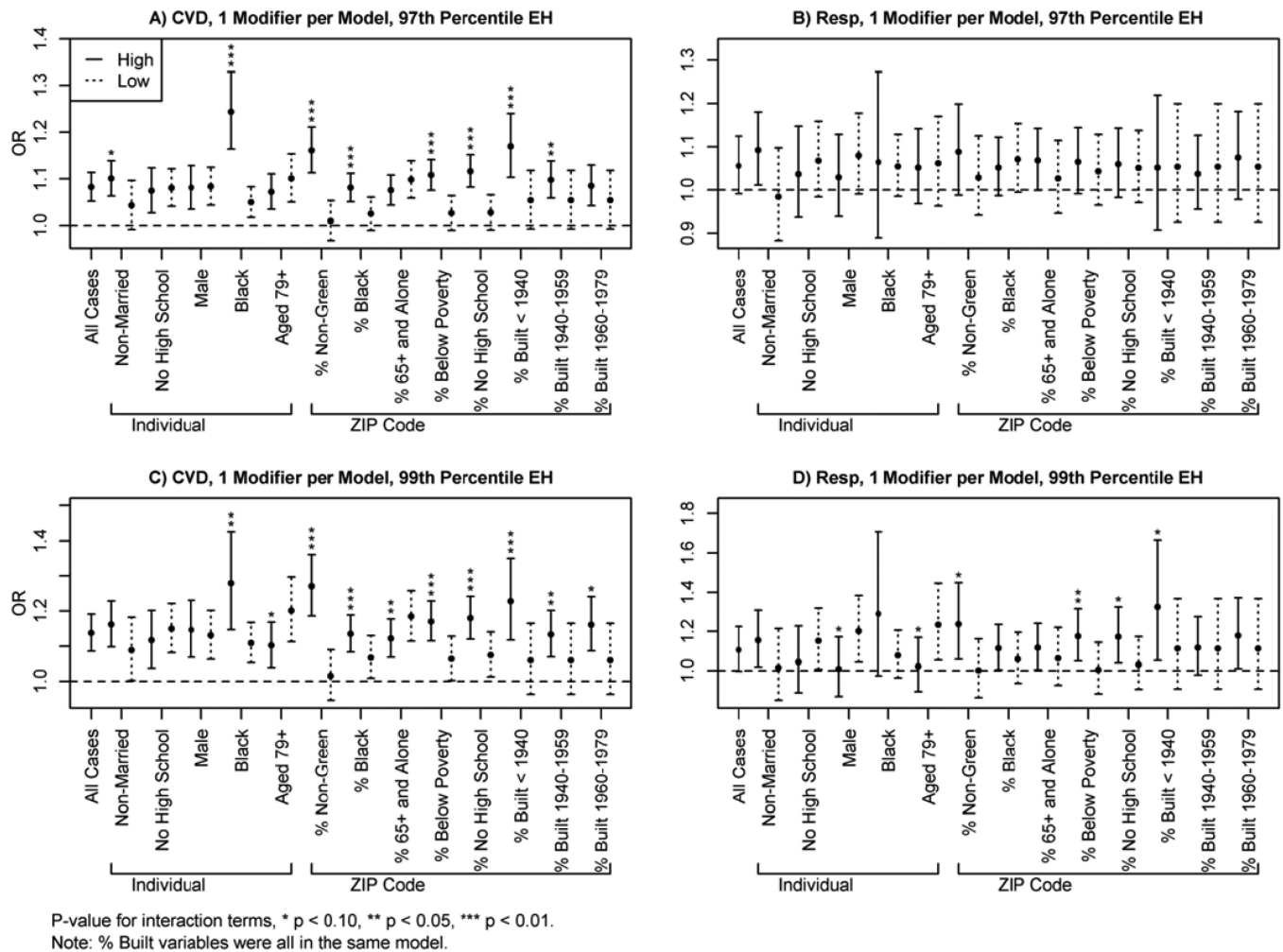
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Highlights

- Characteristics of vulnerability to mortality in extreme heat are often correlated.

- Unmarried and low area green space modify mortality risk in Michigan.

- Area elderly residents living alone and housing age may also modify mortality risk.
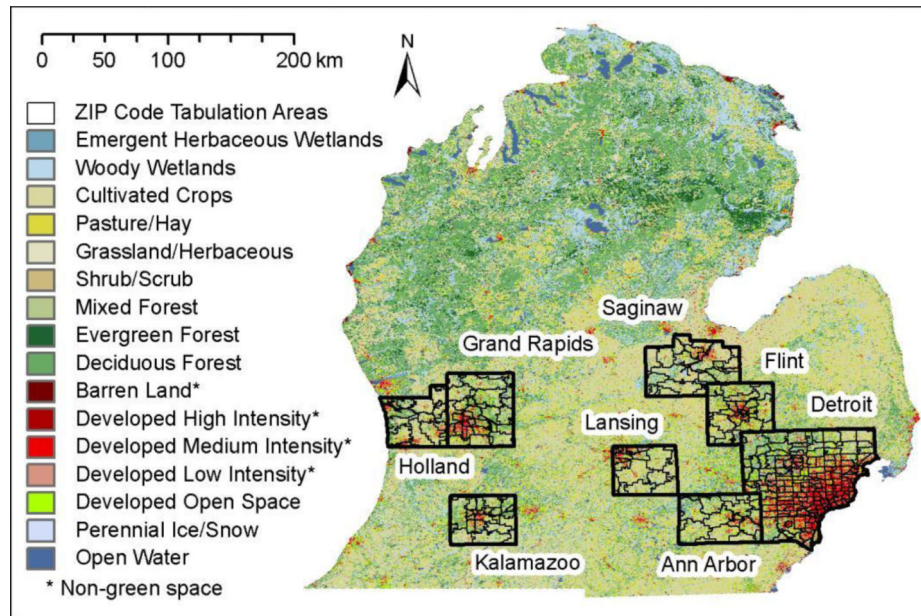
Figure 1.
Land cover in Michigan's Lower Peninsula in 2001 (U.S. Department of the Interior, 2012).
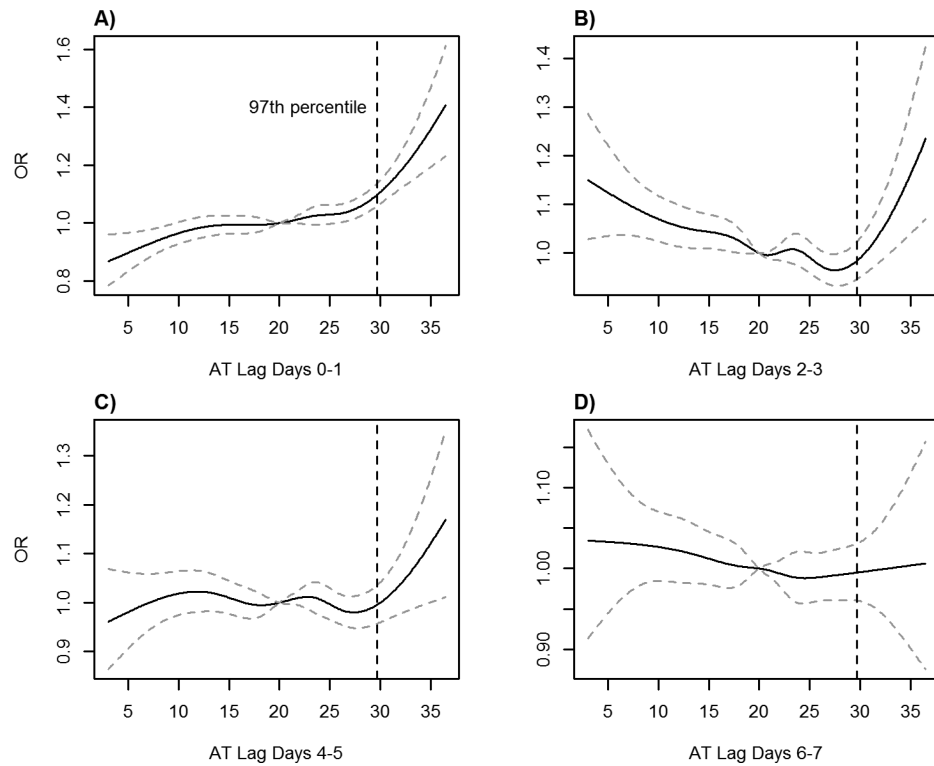
Figure 2.
Odds ratios (ORs) and 95% confidence intervals for the odds of cardiovascular mortality among elderly individuals and 4 2-day lags (lags 0-1, 2-3, 4-5, 6-7) of apparent temperature relative to 20 °C, modeled simultaneously as 4 natural cubic splines (each with 6 degrees of freedom), Detroit, Michigan, 1990-2007. (Dashed line represents the 97th percentile threshold of 2-day apparent temperature in Detroit).

P-value for interaction terms, * p < 0.10, ** p < 0.05, *** p < 0.01.
Note: % Built variables were all in the same model.
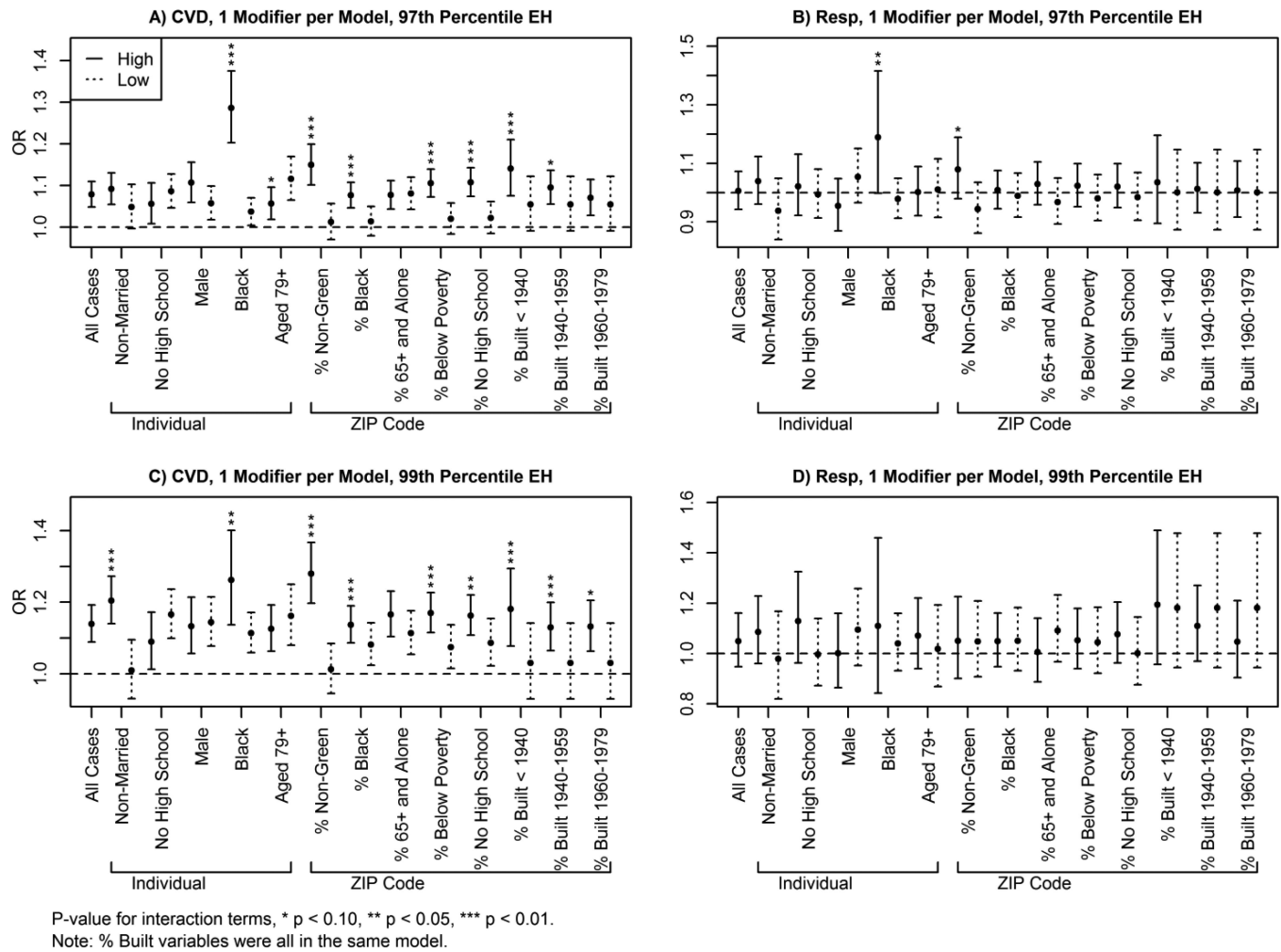
Figure 3.
Odds ratios (ORs) and 95% confidence intervals for the odds of mortality (cardiovascular, CVD, or respiratory, RESP) during extreme heat (EH, the 97th or 99th percentiles of mean apparent temperature over lag days 0-3) vs. non-EH among either all individuals, individuals without (low) or with (high) a given individual characteristic, or individuals residing in ZIP codes in the 25th (low) or 75th (high) percentiles of the ZIP-code characteristic among the elderly in 8 cities in Michigan, May-September, 1990-2007.

Table 1

Individual and Zip Code Tabulation Area characteristics of elderly cases (decedents) in 8 Michigan cities, 1990-2007.

	Ann Arbor	Detroit	Flint	Grand Rapids	Holland	Kalamazoo	Lansing	Saginaw	All cities
Mean daily number of cases, May-September									
All-natural-cause	3.0	62.0	6.5	7.2	2.6	3.3	3.3	3.7	91.6
Cardiovascular	1.0	24.2	2.5	2.5	0.9	1.1	1.2	1.3	34.5
Heat-related	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Respiratory	0.2	4.6	0.5	0.7	0.2	0.3	0.3	0.3	7.1
Percentiles of 4-day mean daily mean apparent temperature (°C)									
97th	27.5	28.3	26.8	27.0	27.0	27.3	26.7	26.5	
99th	29.5	29.9	28.6	28.9	28.9	29.2	28.5	28.5	
Mean daily ozone (ppb)									
Mean over lag days 0-1	ND	43.2	44.8	44.9	ND	ND	45.3	ND	44.5
Percent of cases with the following characteristics									
Non-married	36.5	36.3	38.4	38.5	43.1	38.1	36.5	39.4	37.0
No high school degree	28.5	38.6	40.3	37.2	43.8	33.1	31.4	44.8	38.2
Male	42.7	44.6	44.4	43.5	44.4	42.7	42.0	45.0	44.3
Black	9.7	20.9	13.8	5.3	0.3	5.2	6.2	11.7	16.7
Aged 79+ years	62.3	56.1	54.1	62.5	65.4	61.9	61.2	58.9	42.6
Number of ZIP codes and 25th-75th percentiles of ZIP-code characteristics among the cases[a]									
Number of ZIP codes	26	177	33	39	22	23	23	28	344[b]
% non-green space	8.6-29.7	68.9-94.7	12.1-53.8	43.8-73.9	17.5-24.7	8.7-48.4	25.0-53.3	9.7-46.4	38.7-90.6
% black	3.0-22.8	1.4-49.6	1.7-24.5	1.6-12.2	0.2-1.4	3.7-13.9	2.1-13.5	0.6-15.2	1.4-22.9
% aged 65+ years and living alone	5.0-7.7	8.0-12.7	7.6-11.4	7.2-11.0	6.1-9.9	7.6-10.0	6.8-9.1	9.3-13.0	7.6-12.0
% below poverty level	4.5-14.3	4.3-19.2	6.1-22.6	6.2-12.3	3.7-7.4	6.3-20.6	7.6-20.3	7.7-18.8	4.6-17.5
% without high school degree	4.8-13.0	12.0-27.5	11.9-23.2	11.1-21.4	10.9-17.9	8.1-16.6	7.5-17.0	13.5-24.3	11.1-24.3
% aged 75+ years among those aged 65+	42.1-47.0	40.9-50.2	39.3-45.6	43.2-52.8	44.7-51.6	43.5-50.8	41.4-50.5	40.9-53.7	41.1-50.2

[a] Among all 8 cities combined, the means of percent non-green space, percent black, percent 65 years and older and living alone, percent below the poverty level, percent without a high school degree and percent 75 years and older were 62.3%, 20.6%, 4.9%, 12.5%, 18.6% and 45.7%, respectively.

[b] Some ZIP Code Tabulation Areas lie in more than one city.

Table 2

Correlations (among the elderly cases) between ZIP Code Tabulation Area characteristics in 8 Michigan cities, 1990-2007.

	% Non-Green	% Aged 65+ and Alone	% Below Poverty	% Black	% No High School	% Aged 75+	% Built Before 1940	% Built 1940-1959	% Built 1960-1979
% Non-Green	1.00	0.45	0.40	0.45	0.51	0.18	0.29	0.61	−0.37
% Aged 65+ and Alone		1.00	0.16	0.10	0.25	0.49	0.03	0.09	−0.04
% Below Poverty			1.00	0.78	0.77	0.00	0.72	0.19	−0.48
% Black				1.00	0.59	−0.06	0.52	0.32	−0.44
% No High School					1.00	−0.18	0.62	0.33	−0.43
% Aged 75+						1.00	0.06	0.02	−0.06
% Built Before 1940							1.00	0.11	−0.64
% Built 1940-1959								1.00	−0.58
% Built 1960-1979									1.00

Table 3

Odds ratios (ORs) and 95% confidence intervals for the odds of mortality (cardiovascular or respiratory) during extreme heat (EH03, the 97th or 99th percentiles of mean apparent temperature over lag days 0-3) vs. non-extreme heat in models with or without terms for the mean of ozone over lag days 0-1 (OZ01) or lag days 0-3 (OZ03) among the elderly in 8 Michigan cities or in 4 Michigan cities with ozone monitors (Detroit, Flint, Grand Rapids and Lansing), May-September, 1990-2007.

		Cardiovascular		Respiratory	
Model	N cities	97th percentile EH03	99th percentile EH03	97th percentile EH03	99th percentile EH03
EH03	8	1.08 (1.05-1.11)	1.14 (1.09-1.19)	1.01 (0.94-1.07)	1.05 (0.95-1.16)
EH03	4	1.08 (1.04-1.11)	1.15 (1.10-1.21)	0.99 (0.92-1.06)	1.09 (0.98-1.21)
EH03 + OZ01	4	1.06 (1.02-1.09)	1.13 (1.07-1.18)	0.98 (0.91-1.06)	1.05 (0.94-1.18)
EH03 + OZ03	4	1.05 (1.01-1.08)	1.12 (1.06-1.18)	0.97 (0.90-1.05)	1.06 (0.95-1.19)

Table 4

Odds ratios (ORs) and 95% confidence intervals for the odds of mortality (cardiovascular or respiratory) during extreme heat (EH, the 97th or 99th percentiles of mean apparent temperature over lag days 0-3) vs. non-EH among the elderly in each of 8 Michigan cities, May-September, 1990-2007.

City	Cardiovascular		Respiratory	
	97th percentile EH	99th percentile EH	97th percentile EH	99th percentile EH
Ann Arbor	0.95 (0.79-1.13)	0.89 (0.67-1.20)[*]	0.97 (0.68-1.39)	0.99 (0.56-1.74)
Detroit	1.09 (1.05-1.13)	1.17 (1.11-1.23)	0.98 (0.90-1.06)	1.09 (0.96-1.23)
Flint	0.97 (0.87-1.08)[**]	1.05 (0.88-1.25)	0.99 (0.79-1.24)	0.92 (0.64-1.32)
Grand Rapids	1.08 (0.97-1.20)	1.18 (0.99-1.40)	0.99 (0.80-1.22)	1.21 (0.87-1.68)
Holland	1.10 (0.90-1.33)	0.96 (0.70-1.34)	1.24 (0.89-1.74)	0.82 (0.45-1.50)
Kalamazoo	1.21 (1.02-1.42)	1.13 (0.87-1.48)	1.20 (0.89-1.61)	0.90 (0.53-1.54)
Lansing	1.06 (0.90-1.24)	1.06 (0.82-1.38)	1.27 (0.93-1.73)	1.18 (0.73-1.92)
Saginaw	1.11 (0.96-1.28)	1.11 (0.89-1.39)	1.12 (0.83-1.50)	0.62 (0.34-1.13)[*]

Significance of city-by-EH interaction term (Detroit was reference category):

[*]
$p < 0.10$

[**]
$p < 0.05$

Table 5

Odds ratios (ORs) and 95% confidence intervals for the odds of cardiovascular mortality during extreme heat (EH, the 99th percentile of mean apparent temperature over lag days 0-3) vs. non-EH among elderly individuals without (low) or with (high) a given individual characteristic or elderly individuals residing in ZIP codes in the 25th (low) or 75th (high) percentiles of the ZIP-code characteristic, with multiple interactions per model, in 8 Michigan cities, May-September, 1990-2007.

Characteristic	Model 1		Model 2		Model 3		Model 4	
	Low	High	Low	High	Low	High	Low	High
Non-married	0.98 (0.90-1.07)	1.21 (1.14-1.28)***	0.98 (0.90-1.07)	1.21 (1.14-1.28)***	0.98 (0.90-1.07)	1.21 (1.14-1.28)***	0.98 (0.90-1.07)	1.21 (1.14-1.29)***
No high school	1.09 (1.02-1.17)	1.00 (0.92-1.09)*	1.09 (1.02-1.17)	1.00 (0.92-1.09)*	1.10 (1.02-1.17)	1.00 (0.92-1.09)*	1.10 (1.03-1.18)	1.01 (0.93-1.1)*
Male	1.03 (0.95-1.11)	1.10 (1.02-1.18)	1.03 (0.95-1.11)	1.10 (1.02-1.18)	1.03 (0.95-1.12)	1.10 (1.02-1.18)	1.03 (0.95-1.12)	1.10 (1.03-1.18)
Black	1.06 (0.99-1.13)	1.05 (0.92-1.21)	1.06 (0.99-1.12)	1.06 (0.93-1.21)	1.06 (1.00-1.13)	1.05 (0.92-1.21)	1.06 (1.00-1.13)	1.06 (0.92-1.22)
Age 79+	1.09 (1.01-1.18)	1.03 (0.96-1.11)	1.09 (1.01-1.18)	1.03 (0.96-1.11)	1.09 (1.01-1.18)	1.04 (0.96-1.11)	1.10 (1.01-1.19)	1.04 (0.97-1.12)
% Non-green	0.98 (0.89-1.07)	1.17 (1.06-1.29)**	0.97 (0.89-1.07)	1.17 (1.06-1.29)**	0.97 (0.89-1.05)	1.18 (1.09-1.28)***		
% 65 and alone	1.05 (0.98-1.12)	1.06 (0.99-1.14)	1.05 (0.98-1.12)	1.06 (0.99-1.14)	1.05 (0.99-1.12)	1.06 (0.99-1.14)	1.04 (0.97-1.11)	1.08 (1.01-1.15)
% Below poverty	1.05 (0.97-1.14)	1.06 (0.99-1.14)			1.04 (0.97-1.12)	1.07 (1.00-1.14)	1.04 (0.96-1.12)	1.08 (1.01-1.16)
% Built < 1940[a]	1.03 (0.91-1.16)	1.08 (0.96-1.23)	1.03 (0.92-1.16)	1.09 (0.98-1.22)			0.98 (0.88-1.09)	1.07 (0.94-1.21)
% Built 1940-1959[a]	1.03 (0.91-1.16)	1.05 (0.98-1.13)	1.03 (0.92-1.16)	1.05 (0.98-1.13)			0.98 (0.88-1.09)	1.06 (0.99-1.14)**
% Built 1960-1979[a]	1.03 (0.91-1.16)	1.07 (1.00-1.16)	1.03 (0.92-1.16)	1.08 (1.00-1.16)			0.98 (0.88-1.09)	1.06 (0.99-1.14)

Significance of interaction term:

*
p < 0.10

**
p < 0.05

***
p < 0.001.

[a]Remaining values of % Built variables set to 20% when one set to high (40%).